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Evaluation of two (opx-cpx) pyroxene Geothermometer

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ABSTRACT

In the last few decades, for estimation of the original equilibrium conditions of the mantle and deep crustal rocks, several empirical as well as synthetic thermometers have been proposed. Various types of rocks from earth, moon or meteorites contain two coexisting pyroxenes. Petrologists have long recognised the potential of coexisting high Ca and low Ca pyroxenes to yield thermometric calculations. Several models have been proposed for two pyroxene thermometers in the last few decades. The authors have compared ten models of two pyroxene thermometers proposed since 1973. Sixty one (61) sample data of granulites from the global literature were collected and processed through the "Opx-Cpx.EXE" software. We conclude that three models are the most valid and reliable of this kinds of thermometers: Kretz (1982), Bertrend and Mercier (1985) and Nickel and Green (1985).

Keywords: Exchange reaction, geothermometer, orthopyroxene - clinopyroxene

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INTRODUCTION

Accurate calculation of metamorphic pressure temperature conditions is crucial to understand tectono-metamorphic evolution of a metamorphic terrane. Several thermobarometers have been proposed in the last few decades for a range of temperatures and pressures. Use of mono-equilibrium geothermobarometers (e.g. Ferry and Spear, 1978; Holdaway, 2001) or multi-equilibria geothermobarometers (e.g. Berman, 1991; Powell and Holland, 1994) have always been of major focus. In recent years, great progress have been made in trace element geothermometry, such as Ti in quartz thermometer (Thomas et al., 2010; Wark and Watson, 2006; Wark et al., 2004); Ti in zircon thermometer (Watson, et al., 2006; Ferry and Watson, 2007).

Variety of rock types from the earth, moon and meteorites contain two coexisting pyroxenes. Long back, petrologists have recognised the potential of coexisting high Ca and low Ca pyroxenes to yield thermometric calculations. Several models for two pyroxene (Opx-Cpx) thermometers have been proposed in recent decades. Numerous thermobarometric studies undertaken over the last few decades led to the development of a range of thermometers and barometers, such as garnet-clinopyroxene thermometry (Johnson et al., 1983; Fu et al., 1998), garnet-orthopyroxene thermometry (Thomas et al., 2018), garnet - biotite thermometry (Thomas and Rana, 2019), garnet - cordierite thermometry (Thomas et al., 2020), garnet - hornblende thermometry (Thomas and Rana, 2020).

The study of two pyroxene (Opx - Cpx) thermometry is based on exchange of enstatite component between orthopyroxene and clinopyroxene having a long history (Boyd, 1973; Wood and Banno, 1973; Saxena and Nehru, 1975; Saxena, 1976; Wells, 1977; Kretz., 1982; Lindsley, 1983; Gasparik, 1984; Brey and Kohler, 1990; Taylor, 1998) and till date we now have several versions of two pyroxene thermometers as tabulated in Table 1 e.g. Putirka (2008), Nimis and Grutter (2010) of this geothermometer. Presence of such several versions of geothermometer underscores the need to emphasize the importance of carefully evaluating the thermometer's accuracy and precision. In order to recommend the best calibration for geologists, the authors have compared ten models of two pyroxene thermometers proposed since 1973.

Two pyroxene thermometers

The pyroxene minerals due to their widespread occurrence and great structural and chemical variability are perhaps the most important and interesting of all rock forming minerals (Kretz, 1962). The miscibility gap between orthopyroxene and

Table 1: Models used and their suitable system.

Model	Suitable system
Wood and Banno (1973)	Natural assemblage two pyroxene system
Wells (1977)	Natural assemblage
Kretz (1982)	Ultramafic system
Nickel and Brey (1984)	$CaO-MgO-SiO_2$ system
Nickel and Green (1985)	$CaO-MgO-Al_2O_3-SiO_2$ system
Bertrand and Mercier (1985/86)	Peridotitic system
Brey and Kohler (1990)	Peridotitic system
Taylor (1998)	Peridotitic system
Putirka (2008)	Mafic system
Nimis and Grutter (2010)	Natural system

clinopyroxene is the basis of widely used geothermometers for deep-seated mantle rocks and high grade crustal terrains, mainly granulites and garnet peridotites. Its correct determination is thus crucial for estimating pressure temperature distributions in the earth's crust and mantle. Quantification of orthopyroxene-clinopyroxene Fe-Mg equilibrium is widely applied thermometer for granulite, and granulitised eclogite facies assemblages as well as garnet peridotites, whereas the distribution of the Fe^{+2} and Mg between coexisting orthopyroxene and clinopyroxene is expressed by the reaction (Eq. 1).

$$Mg_2Si_2O_6\ (Opx) = Mg_2Si_2O_6\ (Cpx) \qquad (1)$$

The authors have summarized below the two pyroxene thermometers used in this comparative study:

Wood and Banno (1973): Wood and Banno (1973) proposed an empirical approach to take an account of Fe^{2+} on the orthopyroxene-clinopyroxene miscibility gap in natural system in order to calculate equilibration temperature of two pyroxene thermometer formulating the Equation 2.

$$T(°K) = \frac{-10202}{\left[\ln\left(\frac{a^{Cpx}_{Mg_2Si_2O_6}}{a^{Opx}_{Mg_2Si_2O_6}}\right) - 7.65\times Fe^{Opx} + 3.88*(X^{Opx}_{Fe})^2 - 4.6\right]} \qquad (2)$$

$$\text{where, } K_D = \frac{(X^{M1}_{Mg}X^{M2}_{Mg})Cpx}{(X^{M1}_{Mg}X^{M2}_{Mg})Opx}$$

Wells (1977): Wells (1977) considered solid solutions and a semi-empirical equation of state extracted from the available experimental data for the diopside-enstatite miscibility gap. This equation successfully reproduces the miscibility gap over a temperature range of 800ºC to 1700ºC and is apparently also applicable to aluminous pyroxenes in the system $CaSiO_3$-$MgSiO_3$-Al_2O_3 giving the Equation 3.

$$T(°K) = \frac{7341}{\left(3.355 + 2.44*X^{Opx}_{Fe} - \ln_{K_D}\right)} \qquad (3)$$

$$\text{where, } K_D = \frac{(X^{M1}_{Mg}X^{M2}_{Mg})Cpx}{(X^{M1}_{Mg}X^{M2}_{Mg})Opx}$$

Kretz (1982): Kretz opined that the differences in the chemical composition of metamorphic and igneous pyroxene minerals may be attributed by a transfer reaction, which determines the Ca content of the minerals, and an exchange reaction, which determines the relative Mg/Fe^{2+} ratios. Equation 4 is for the temperature - dependence of the Mg-Fe distribution coefficient.

$$T(°C) = \frac{1130}{(\ln K_D + 0.505)} \qquad (4)$$

$$\text{where, } K_D = \frac{X_{Opx}}{1-X_{Opx}} \Big/ \frac{X_{Cpx}}{1-X_{Cpx}}$$

Nickel and Brey (1984): Nickel and Brey (1984) gave a regular solution model with two independent regular solutions for Opx and Cpx capable of reproducing experimental data in the system CaO-MgO-SiO_2 over a large range of temperature and pressures. The stability region is valid for Fe-free low-Ca pyroxene (Eq. 5, 6).

$$T_A(°K) = \frac{\left[-7 - P(Kbar)*0.06188 + 34*(X^{Opx}_{D_i})^2 - (21.905 - P(Kbar)*0.05229)*(X^{Cpx}_{D_i})^2\right]}{\left[0.0083143*\ln k_D(A) + 0.004431*(X^{Cpx}_{D_i})^2 - 0.00397\right]} \qquad (5)$$

$$\text{where, } K_D = \frac{X^{Cpx}_{En}}{X^{Opx}_{En}}$$

$$T_B(°K) = \frac{\left[(12.909 + P(Kbar)*0.1633 + 34*(X^{Cpx}_{En})^2 - (20.905 - P(Kbar)*(0.05229*(X^{Cpx}_{En})^2\right]}{\left[0.0083143*\ln K_D(B) + 0.004431*(X^{Cpx}_{En})^2 + 0.0085\right]} \qquad (6)$$

$$\text{where, } K_D = \frac{X^{Cpx}_{En}}{X^{Opx}_{En}}$$

Nickel and Green (1985): They proposed a thermometer for co-existing orthopyroxene and clinopyroxene in the CMAS system, at 1000ºC to 1570ºC and 30 kbar – 50 kbar conditions (Eq. 7).

$$T(°C) = [1616.67 + 287.935 * \ln K_D + 2.933P(Kbar)] \qquad (7)$$

$$\text{where, } K_D = \frac{(1-Al/2)*(1-Ca)^{Cpx}}{(1-Al/2)*(1-Ca)^{Opx}}$$

Bertrand and Mercier (1985/86): This geothermometer is directly applicable to the natural system as illustrated by the remarkable agreement between the experiment conditions and the calculated temperatures for re-equilibration experiments on natural systems of CMS and CMAS systems (Eq. 8).

$$T(°K) = \frac{[36273 + 399*P(Gpa)]}{\left[19.31 - 8.314*\ln K^* - 12.15(Ca^*_{Cpx})^2\right]} \qquad (8)$$

$$\text{where, } K_D = \frac{1 - Ca^{Cpx}}{1 - Ca^{Opx}}$$

Brey and Kohler (1990): This thermometer can be applied both to the CMS and the natural system experiments which may indicate that Fe and Na have counter balancing effects on the Ca content of orthopyroxene (Eq. 9, 10).

$$T_A(°K) = \frac{\left[23664+(24.9+126.3*X_{Fe}^{Cpx})*P(Kbar)\right]}{\left[13.38+(\ln K_D^*)^2+11.59*X_{Fe}^{Opx}\right]} \quad (9)$$

where, $KD = \frac{1- Ca^{Cpx}}{1- Ca^{Opx}}$

$$T_B(°K) = \frac{[35000+61.5*P(Kbar)]}{[(\ln D_{Na})^2+19.8]} \quad (10)$$

Taylor (1998): This thermometer model is modified form of the Brey and Kohler (1990) is based on mineral chemical data from a series of P-T, fo_2 controlled fluid-saturated experiments in the range of P=1.0 to 3.5 Gpa and T = 1050 to 1260ºC. It is applicable to a wide range of fertile peridotitic compositions (Eq. 11).

$$T(°K) = \frac{[24787+678*P(GPa)]}{[15.67+14.37*Ti^{Cpx}+3.69*Fe^{Cpx}-3.25*X_{ts}+(\ln K_D)^2]} \quad (11)$$

where, $K_D = \frac{a_{Cpx}^{En}}{a_{Opx}^{En}}$

Putirka (2008): Introduced two-pyroxene thermometer for mafic systems based on the partition of enstatite + ferrosilite between orthopyroxene and clinopyroxene by using a new global regression model (Eq. 12, 13).

$$T_{p1}(°C) = \frac{10000}{11.2-1.96*\ln\left(\frac{X_{EnFs}^{Cpx}}{X_{EnFs}^{Opx}}\right)-3.3*\left(X_{Ca}^{Cpx}\right)-25.8*\left(X_{CrCaTs}^{Cpx}\right)+33.2*\left(X_{Mn}^{Opx}\right)-. \quad 23.6*\left(X_{Na}^{Opx}\right)-2.08*\left(X_{En}^{Opx}\right)-8.33*\left(X_{Di}^{Opx}\right)-0.05*P(Kbar)} \quad (12)$$

$$T_{p2}(°C) = \frac{10000}{13.4-3.4*\ln\left(\frac{X_{EnFs}^{Cpx}}{X_{EnFs}^{Opx}}\right)+5.59*\left(X_{Mg}^{Cpx}\right)-8.8*\left(Mg\#^{Cpx}\right)+23.85*\left(X_{Mn}^{Opx}\right) \quad +6.48*\left(X_{FmAl_2Sio_6}^{Opx}\right)-2.38*\left(X_{Di}^{Cpx}\right)-0.044*P(Kbar)} \quad (13)$$

where, $K_D = \frac{EnFs^{Cpx}}{EnFs^{Opx}}$

Nimis and Grutter (2010): They worked to improve the internal consistency between two-pyroxene and Ca-in Opx models of Brey and Kohler (1990) for temperature of mantle derived rocks and proposed the following empirical correction (Eq. 14).

$$T(°C) = [-628.7 + 2.0690 * (TBK) - 4.530 * 10^{-4} * (TBK)^2] \quad (14)$$

where, $K_D = \frac{1- Ca^{Cpx}}{1- Ca^{Opx}}$

RESULT AND DISCUSSION

Sixty-one pairs of data for orthopyroxene (Table 2) and for clinopyroxene parameters (Table 3) respectively in specific format were processed for the validation of the software (Thomas, 1994) and different models of orthopyroxene - clinopyroxene pair and the results are shown in Table 4 along with the calculation of temperatures of different models.

The relationship of $\ln K_D$ and inverse of temperature has been checked for the ten models and the regression coefficient based on the best fit lines has been calculated. This method has been used to check the dependence of temperature on elemental partitioning and distribution coefficient tabulated in Table 5. The plots of $\ln K_D$ vs 1/T are shown in Figures 1 to 10.

Since the advent of geothermobarometry in metamorphic petrology, proper evaluation of metamorphic temperatures has been a matter of discussion. Various methods were used to determine precise temperatures. Some researchers determine temperature by averaging the results from all applicable thermometers. Additionally, a small number of researchers also used consensus peak temperature in which a temperature is chosen where the spreads in temperatures from each thermometer overlap. Averaging results from different thermometers can be completely unjustified yielding only an approximation of temperature, although the use of consensus temperature is feasible for evaluating temperature variation within a terrane. With the above considerations, the present study attempted to evaluate the accuracy of ten models taking each separately and checking the regression and scattering of temperature values. Considering the regression plots of various models of two pyroxene thermometer, the dependency of lnkd versus inverse of temperature have shown that the maximum regression values are shown by the following models: Kretz (1982), Bertrend and Mercier (1985) and Nickel and Green (1985). This shows that the best fit line for the range of temperature calculated for these models are showing the maximum linear values within a shorter range of temperature variation for each model.

Table 2: Data of orthopyroxene parameter of different rock samples by different researchers.

Data of different researchers	$(X_{Mg}^{M_1})_{Opx}$	$(X_{Mg}^{M_2})_{Opx}$	X_{Opx}^{Fe}	X_{En}^{Opx}	Ca_{Opx}^{*}	$a(En)^{Opx}$	Al_{iV}^{Opx}	Al_{Vi}^{Opx}	X_{EnFs}^{Opx}	X_{En}^{Opx}	X_{Di}^{Opx}	X_{Mn}^{Opx}	X_{Na}^{Opx}
Appel et al. (1998)	0.622	0.615	0.365	0.984	0.02	0.904	0.04	0.04	0.975	0.615	0.016	0.007	0.001
Baldwin et al. (2003)	0.581	0.575	0.413	1	0	0.941	0.03	0.01	0.977	0.573	0	0.008	0.006
Barnicoat (1983)	0.564	0.552	0.431	0.982	0.02	0.941	0.02	0.02	0.963	0.544	0.018	0.012	0.001
Barth and May (1992)	0.523	0.505	0.472	0.972	0.029	0.924	0.028	0.018	0.951	0.498	0.028	0.016	0
Brodie (1995)	0.77	0.79	0.194	0.987	0.02	0.788	0.12	0.09	0.88	0.709	0.013	0.002	0
Carney et al. (1991)	0.546	0.47	0.454	0.885	0.13	0.853	0.02	0	0.842	0.457	0.115	0.007	0
Cooke (2000)	0.6	0.583	0.396	0.979	0.025	0.945	0.016	0.014	0.96	0.577	0.021	0.009	0
Cruciani et al. (2012)	0.516	0.493	0.487	0.98	0.02	0.96	0.02	0	1.013	0.477	0.02	0.019	0.001
Daczko and Halpin (2009)	0.593	0.599	0.382	0.992	0.01	0.805	0.12	0.08	0.916	0.561	0.008	0.02	0.001
Yoshida et al,(2004)	0.899	0.909	0.085	0.996	0.007	0.902	0.056	0.021	0.976	0.893	0.004	0	0
Dasgupta et al. (1992)	0.785	0.718	0.211	0.925	0.05	0.903	0.04	0.01	0.929	0.298	0.075	0.038	0
Ellis and Green (1985)	0.667	0.679	0.3	0.986	0.019	0.798	0.098	0.1	0.878	0.611	0.014	0.011	0
El-Shazly et al (2011)	0.559	0.564	0.424	0.991	0.01	0.84	0.09	0.07	0.921	0.527	0.009	0.01	0
Elvevold et al (2003)	0.786	0.782	0.202	0.994	0.01	0.922	0.04	0.03	0.958	0.755	0.006	0.011	0.003
Joshi et al. (1993)	0.597	0.588	0.403	0.988	0.015	0.984	0	0	0.963	0.573	0.012	0.008	0
Engvik et al., (2007)	0.569	0.555	0.422	0.982	0.02	0.913	0.04	0.03	0.95	0.541	0.018	0.02	0
Gallien et al., (2012)	0.766	0.746	0.223	0.98	0.03	0.876	0.06	0.03	0.935	0.724	0.02	0.011	0.001
Garde (1990)	0.55	0.524	0.442	0.972	0.03	0.904	0.04	0.03	0.941	0.516	0.028	0.028	0
Goto and Bano (1990)	0.742	0.759	0.222	0.991	0.014	0.8	0.107	0.089	0.899	0.696	0.009	0.009	0
Grant (1989)	0.734	0.749	0.244	0.993	0.01	0.867	0.07	0.06	0.925	0.679	0.007	0.004	0
Griffin et al. (1979)	0.601	0.601	0.387	0.984	0.019	0.933	0.01	0.039	0.942	0.577	0.016	0	0
Harley (1988)	0.382	0.355	0.617	0.936	0.051	0.891	0.053	0.002	0.953	0.361	0.064	0.02	0.002
Jamtveit et al. (1991)	0.848	0.839	0.152	0.994	0.01	0.97	0	0.02	0.98	0.828	0.006	0.004	0
Kardarusman and Parkinson (2000)	0.92	0.902	0.098	1	0	0.941	0.03	0.03	0.952	0.858	0	0.005	0
Liangzhao and Jenkins (1993)	0.583	0.571	0.417	0.991	0.01	0.912	0.08	0	1.002	0.58	0.009	0.006	0.004
Loock et al. (1990)	0.675	0.664	0.309	0.982	0.025	0.872	0.062	0.043	0.935	0.642	0.018	0.011	0.003
Lucassen and Franz (1996)	0.613	0.586	0.383	0.975	0.03	0.951	0.01	0.01	0.953	0.584	0.025	0.02	0.001
Mahan et al. (2008)	0.623	0.611	0.377	0.992	0.01	0.931	0.06	0	0.99	0.614	0.008	0.01	0
Marschall et al. (2003)	0.488	0.469	0.507	0.973	0.026	0.906	0.044	0.023	0.949	0.459	0.027	0.021	0.002
Muhling (1990)	0.637	0.625	0.355	0.987	0.016	0.926	0.034	0.024	0.963	0.613	0.013	0.014	0.001
Muhongo and Tuisku (1996)	0.629	0.623	0.357	0.984	0.02	0.865	0.078	0.038	0.949	0.607	0.016	0.008	0.002
Raith et al. (1983)	0.492	0.486	0.499	0.981	0.019	0.934	0.011	0.035	0.938	0.467	0.019	0.01	0
Rao et al. (1997)	0.476	0.463	0.523	0.976	0.022	0.942	0.029	0	0.922	0.438	0.024	0.006	0.002
Sengupta et al (1999)	0.765	0.769	0.207	0.987	0.02	0.002	1.91	0.05	1.005	0.779	0.013	0.007	0.001
Sharma et al. (1987)	0.647	0.578	0.365	0.936	0.083	0.897	0.008	0	0.902	0.571	0.064	0.007	0
Stephenson (1984)	0.481	0.448	0.519	0.965	0.033	0.917	0.049	0	0.943	0.445	0.035	0.035	0
Stuwe and Powell (1989)	0.461	0.477	0.514	0.994	0.005	0.834	0.065	0.095	0.868	0.42	0.006	0.007	0.006
Stuwe and Powell (1989)	0.409	0.397	0.591	0.98	0.016	0.984	0	0	0.927	0.377	0.02	0.014	0
Tong and Wilson (2006)	0.553	0.533	0.447	0.98	0.021	0.864	0.118	0	0.918	0.504	0.02	0.015	0
Ulianov and Kalt (2006)	0.842	0.828	0.142	0.994	0.011	0.92	0.033	0.034	0.972	0.834	0.006	0.002	0.003
Warren et al. (2012)	0.612	0.593	0.388	0.983	0.02	0.903	0.08	0	0.971	0.568	0.017	0.014	0.001
William et al. (2000)	0.395	0.381	0.603	0.963	0.03	0.932	0.03	0.01	0.949	0.375	0.038	0.012	0.002
Zheng et al. (2006)	0.584	0.564	0.407	0.971	0.033	0.795	0.062	0.031	0.941	0.542	0.029	0.016	0.001
Thomas (2005)	0.597	0.584	0.403	0.988	0.014	0.941	0.045	0	0.963	0.573	0.012	0.008	0
Groppo et al. (2007)	0.485	0.475	0.505	0.979	0.02	0.941	0	0.04	0.958	0.469	0.021	0.019	0
St-Onge and Lucas (1995)	0.501	0.483	0.487	0.97	0.03	0.922	0	0.05	0.91	0.463	0.03	0.025	0
Attoh (1998)	0.585	0.597	0.403	1	0	0.922	0.04	0.04	0.959	0.572	0	0.011	0.003
Baba (1998)	0.631	0.628	0.359	0.992	0.01	0.904	0.06	0.03	0.966	0.616	0.008	0.014	0.004
Janak et al. (2006)	0.884	0.888	0.103	0.994	0.01	0.922	0.03	0.04	0.949	0.852	0.006	0.003	0
Jones and Escher (2002)	0.612	0.6	0.388	0.991	0.01	0.794	0.2	0	0.854	0.52	0.009	0.014	0
Klonowska et al. (2015)	0.91	0.914	0.077	0.995	0.01	0.932	0.03	0.03	0.961	0.887	0.005	0.001	0
Lamb et al. (1986)	0.437	0.423	0.558	0.97	0.027	0.926	0.023	0.024	0.946	0.423	0.03	0.016	0
Palmeri et al. (2007)	0.88	0.871	0.116	0.995	0.008	0.954	0.028	0.004	0.986	0.86	0.005	0.002	0.005
St-Onge and Lucas (1995)	0.519	0.511	0.468	0.98	0.02	0.931	0	0.05	0.915	0.483	0.02	0.021	0
Ackermand et al. (1987)	0.663	0.636	0.337	0.984	0.02	0.928	0.05	0	0.979	0.626	0.016	0.022	0.001
Liogys and Jenkins (2000)	0.567	0.53	0.432	0.976	0.027	0.941	0.029	0	0.337	0.014	0.024	0.045	0

Data of different researchers	$(X_{Mg}^{M_1})_{Opx}$	$(X_{Mg}^{M_2})_{Opx}$	X_{Opx}^{Fe}	X_{En}^{Opx}	Ca_{Opx}^{*}	$a(En)^{Opx}$	Al_{iV}^{Opx}	Al_{Vi}^{Opx}	X_{EnFs}^{Opx}	X_{En}^{Opx}	X_{Di}^{Opx}	X_{Mn}^{Opx}	X_{Na}^{Opx}
Mukhopadhyay and Bhattachrya (1997)	0.465	0.447	0.535	0.967	0.03	0.941	0.03	0	1.012	0.434	0.033	0.012	0.002
Bohlen and Essene (1978)	0.577	0.558	0.423	0.985	0.017	0.955	0.027	0	0.954	0.538	0.015	0.017	0.001
Tenthorey et al. (1996)	0.864	0.869	0.122	0.994	0.01	0.904	0.06	0.03	0.96	0.84	0.006	0.005	0.001
Thost et al. (1991)	0.637	0.646	0.34	0.992	0.01	0.857	0.07	0.07	0.925	0.605	0.008	0.014	0
Bohlen and Essene (1979)	0.247	0.23	0.753	0.923	0.039	0.933	0.025	0	0.933	0.227	0.077	0.031	0.002

Table 3: Data of clinopyroxene parameter of different rock sample by different researchers.

Data of different researchers	$(X_{Mg}^{M_1})_{Cpx}$	$(X_{Mg}^{M_2})_{Cpx}$	X_{Fe}^{Cpx}	X_{En}^{Cpx}	Ca_{Cpx}^{*}	X_{ts}^{Cpx}	$a(En)^{Cpx}$	Al_{iV}^{Cpx}	Al_{Vi}^{Cpx}	X_{EnFs}^{Cpx}	X_{CrCaTs}^{Cpx}	X_{Ca}^{Cpx}
Appel et al. (1998)	0.723	0.046	0.235	0.47	0.819	-0.01	0.054	0.05	0.05	0.085	0.001	0.877
Baldwin et al. (2003)	0.754	0.054	0.231	0.468	0.814	0	0.065	0.04	0.02	0.078	0.001	0.905
Barnicoat (1983)	0.706	0.03	0.253	0.451	0.832	-0.01	0.037	0.02	0.05	0.052	0	0.899
Barth and May (1992)	0.656	0.072	0.318	0.455	0.726	0.021	0.1	0.057	0.048	0.117	0	0.86
Brodie (1995)	0.803	0.017	0.136	0.45	0.911	0.04	0.014	0.19	0.09	0.03	0	0.94
Carney (1991)	0.621	0.115	0.363	0.477	0.634	-0.01	0.164	0.04	0.02	0.176	0	0.788
Cooke (2000)	0.715	0.068	0.249	0.468	0.779	0.023	0.083	0.047	0.06	0.092	0	0.869
Cruciani et al. (2012)	0.683	0.035	0.3	0.435	0.789	-0.01	0.057	0.03	0.01	0.08	0.001	0.909
Daczko and Halpin (2009)	0.589	0.034	0.311	0.434	0.776	0.03	0.044	0.11	0.16	0.132	0	0.812
Yoshida et al. (2004)	0.807	0.033	0.067	0.502	0.927	0.009	0.03	0.019	0.118	0.044	0.011	0.834
Dasgupta et al. (1992)	0.427	0.052	0.569	0.353	0.577	0.02	0.126	0.07	0.02	0.135	0	0.864
Ellis and Green (1985)	0.747	0.054	0.211	0.437	0.826	0.106	0.05	0.184	0.102	0.066	0.002	0.942
El-Shazly et al. (2011)	0.568	0.498	0.336	0.871	-0.002	0.11	0.565	0.06	0.19	0.736	0.003	0.153
Elvevold et al. (2003)	0.897	0.036	0.098	0.492	0.911	-0.01	0.039	0.02	0	0.047	0.002	0.951
Joshi et al. (1993)	0.706	0.069	0.27	0.46	0.76	-0.067	0.096	0	0	0.079	0	0.853
Engvik et al. (2007)	0.684	0.064	0.284	0.444	0.753	-0.01	0.086	0.1	0.04	0.119	0.001	0.855
Gallien et al. (2012)	0.837	0.034	0.141	0.472	0.88	0.05	0.041	0.13	0.05	0.065	0.003	0.95
Garde (1990)	0.636	0.054	0.323	0.438	0.745	0.02	0.079	0.05	0.07	0.092	0	0.862
Goto and Bano (1990)	0.765	0.036	0.168	0.459	0.867	0.081	0.036	0.121	0.113	0.06	0.004	0.913
Grant (1989)	0.774	0.024	0.206	0.463	0.867	-0.01	0.028	0.04	0.02	0.07	0	0.936
Griffin et al. (1979)	0.712	0.069	0.244	0.467	0.782	0.001	0.081	0.051	0.059	0.083	0	0.859
Harley (1988)	0.479	0.066	0.505	0.389	0.604	0.029	0.126	0.071	0.048	0.144	0	0.839
Jamtveit et al. (1991)	0.762	0.053	0.12	0.5	0.872	0.01	0.052	0	0.12	0.058	0.007	0.814
Kardarusman and Parkinson (2000)	0.767	0.102	0.076	0.528	0.836	0.08	0.087	0	0.14	0.094	0.017	0.755
Liangzhao and Jenkins (1993)	0.609	0.012	0.382	0.42	0.779	-0.03	0.027	0.1	0	0.107	0	0.942
Loock et al. (1990)	0.698	0.048	0.245	0.45	0.808	0.051	0.052	0.125	0.101	0.081	0	0.883
Lucassen and Franz (1996)	0.778	0.032	0.206	0.456	0.846	-0.02	0.046	0.06	0.01	0.068	0	0.925
Mahan et al. (2008)	0.711	0.052	0.26	0.464	0.798	0	0.064	0.05	0.04	0.087	0.002	0.886
Marschall et al. (2003)	0.659	0.059	0.318	0.442	0.743	-0.003	0.088	0.043	0.029	0.1	0	0.873
Muhling (1990)	0.725	0.047	0.235	0.459	0.814	0.005	0.06	0.038	0.055	0.07	0	0.886
Muhongo and Tuisku (1996)	0.654	0.042	0.284	0.452	0.791	0.008	0.05	0.095	0.091	0.091	0	0.855
Raith et al. (1983)	0.539	0.055	0.41	0.409	0.692	0.029	0.085	0.021	0.1	0.086	0	0.831
Rao et al. (1997)	0.486	0.196	0.488	0.527	0.36	0.057	0.336	0.056	0.076	0.376	0.001	0.59
Sengupta et al. (1999)	0.886	0.046	0.087	0.475	0.896	0.04	0.047	0.17	0.05	0.09	0.001	0.933
Sharma et al. (1987)	0.782	0.228	0.193	0.579	0.61	0.014	0.257	0.062	0	0.282	0.018	0.689
Stephenson (1984)	0.613	0.063	0.373	0.43	0.698	-0.003	0.105	0.06	0.021	0.103	0	0.871
Stuwe and Powell (1989)	0.604	0.043	0.347	0.416	0.739	-0.001	0.065	0.067	0.037	0.057	0	0.903
Stuwe and Powell (1989)	0.571	0.073	0.429	0.399	0.65	0	0.137	0	0	0.075	0	0.913
Tong and Wilson (2006)	0.651	0.06	0.337	0.41	0.739	0.035	0.077	0.151	0.033	0.07	0.001	0.927
Ulianov and Kalt (2006)	0.749	0.051	0.11	0.485	0.877	0.076	0.044	0.092	0.196	0.065	0	0.819
Warren et al. (2012)	0.732	0.052	0.253	0.444	0.792	-0.02	0.071	0.1	0.01	0.104	0	0.897
William et al. (2000)	0.512	0.042	0.472	0.392	0.681	-0.04	0.073	0.08	0.01	0.116	0	0.885

Data of different researchers	$\left(X_{Mg}^{M_1}\right)_{Cpx}$	$\left(X_{Mg}^{M_2}\right)_{Cpx}$	X_{Fe}^{Cpx}	X_{En}^{Cpx}	Ca_{Cpx}^{*}	X_{ts}^{Cpx}	$a(En)^{Cpx}$	Al_{iV}^{Cpx}	Al_{Vi}^{Cpx}	X_{EnFs}^{Cpx}	X_{CrCaTs}^{Cpx}	X_{Ca}^{Cpx}
Zheng et al. (2006)	0.657	0.064	0.302	0.442	0.747	0.018	0.084	0.077	0.067	0.116	0	0.852
Thomas (2005)	0.702	0.069	0.27	0.46	0.76	-0.056	0.088	0.077	0.011	0.079	0	0.853
Groppo et al. (2007)	0.697	0.035	0.303	0.421	0.799	0	0.048	0.04	0	0.031	0	0.969
St-Onge and Lucas (1995)	0.633	0.061	0.326	0.424	0.735	0.06	0.091	0	0.09	0.07	0.002	0.873
Attoh (1998)	0.571	0.028	0.308	0.45	0.798	-0.03	0.031	0.08	0.16	0.083	0	0.771
Baba (1998)	0.698	0.129	0.284	0.509	0.675	0.01	0.161	0.07	0.03	0.202	0.001	0.796
Janak et al. (2006)	0.841	0.145	0.096	0.534	0.789	0.1	0.127	0.1	0.11	0.16	0.002	0.821
Jones and Escher (2002)	0.468	0.048	0.351	0.358	0.626	-0.03	0.098	0.1	0	0.09	0	0.864
Klonowska et al. (2015)	0.94	0.058	0.041	0.5	0.92	0.04	0.057	0.01	0.04	0.029	0.002	0.943
Lamb et al. (1986)	0.575	0.055	0.405	0.413	0.697	0.011	0.09	0.056	0.039	0.113	0	0.873
Palmeri et al. (2007)	0.869	0.047	0.089	0.5	0.901	0.006	0.046	0.007	0.049	0.042	0.002	0.908
St-Onge and Lucas (1995)	0.616	0.026	0.351	0.401	0.773	0.02	0.043	0.07	0.06	0.039	0.002	0.906
Ackermand et al. (1987)	0.757	0.062	0.22	0.47	0.798	0	0.083	0.05	0.03	0.103	0	0.89
Liogys and Jenkins (2000)	0.685	0.021	0.291	0.455	0.809	-0.068	0.041	0.042	0	0.085	0	0.889
Mukhopadhyay and Bhattachrya (1997)	0.578	0.065	0.413	0.415	0.672	-0.01	0.111	0.06	0.01	0.133	0	0.868
Bohlen and Essene (1978)	0.704	0.057	0.27	0.444	0.776	0.015	0.077	0.044	0.044	0.098	0	0.888
Tenthorey et al. (1996)	0.902	0.038	0.06	0.5	0.929	0.04	0.033	0.08	0.06	0.057	0.001	0.938
Thost et al. (1991)	0.716	0.09	0.25	0.463	0.746	0.09	0.041	0.09	0.09	0.106	0	0.869
Bohlen and Essene (1979)	0.387	0.221	0.606	0.497	0.103	-0.036	0.568	0.011	0	0.088	0	0.895

Table 4: **Data of the calculated temperature T (ºC) of different rock samples by different researchers.**

Data of different researchers	Wood and Banno (1973)	Wells (1977)	Kretz (1982)	Nickel and Brey (1984)	Nickel and Green (1985)	Bertrand and Mercier (1985/86)	Brey and Kohler (1990)	Taylor (1998)	Putirka (2008)	Nimis and Grutter (2010)
	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)
Appel et al. (1998)	821	824	725	1246	1031	1182	686	765	926	577
Baldwin et al. (2003)	835	861	559	1225	942	1180	683	796	864	574
Barnicoat (1983)	761	761	589	1255	976	1162	584	661	794	425
Barth and May (1992)	851	904	706	1266	1075	1293	759	889	883	681
Brodie (1995)	777	692	950	1249	877	983	516	512	787	318
Carney (1991)	920	1005	1008	1357	1225	1423	876	978	1012	836
Cooke (2000)	862	894	677	1253	1052	1238	761	854	877	683
Cruciani et.al. (2012)	771	790	597	1263	948	1223	631	755	823	497
Daczko and Halpin (2009)	766	753	1105	1248	1150	1233	695	740	894	591
Yoshida et al. (2004)	906	776	1208	1218	1108	928	697	651	845	593
Dasgupta et al. (1992)	826	760	923	1332	1084	1394	702	890	825	601
Ellis and Green (1985)	866	857	884	1255	872	1170	732	797	862	643
El-Shazly et al. (2011)	1133	1359	1008	1294	1575	1636	1044	1183	1025	1038
Elvevold et al (2003)	870	808	563	1225	782	981	649	705	828	523
Joshi et al. (1993)	857	889	747	1245	1124	1252	772	855	847	699
Engvik et al. (2007)	847	882	742	1257	1095	1262	759	862	880	681
Gallien et al. (2012)	848	793	794	1250	780	1072	695	724	880	590
Garde (1990)	818	846	844	1271	1074	1276	736	840	824	648
Goto and Bano (1990)	844	787	1054	1241	934	1093	687	720	858	579
Grant (1989)	887	727	508	1236	836	1092	527	630	883	336
Griffin et al. (1979)	863	893	687	1249	1091	1231	762	852	882	685

Data of different researchers	Wood and Banno (1973)	Wells (1977)	Kretz (1982)	Nickel and Brey (1984)	Nickel and Green (1985)	Bertrand and Mercier (1985/86)	Brey and Kohler (1990)	Taylor (1998)	Putirka (2008)	Nimis and Grutter (2010)
	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)	T°(c)
Harley (1988)	824	889	898	1322	1120	1389	736	916	881	648
Jamtveit et al. (1991)	920	839	1167	1221	1147	1082	803	760	853	741
Kardarusman and Parkinson (2000)	1056	959	1173	1202	1210	1146	999	920	943	986
Liangzhao and Jenkins (1993)	662	626	1460	1252	830	1229	527	579	924	335
Loock et al. (1990)	838	823	1099	1256	1018	1201	735	760	879	648
Lucassen and Franz (1996)	785	780	547	1262	919	1142	635	715	824	503
Mahan et al. (2008)	828	838	803	1238	999	1206	707	795	869	608
Marschall et al. (2003)	830	881	601	1269	1056	1275	711	866	845	614
Muhling (1990)	827	828	764	1245	1017	1188	708	784	834	609
Muhongo and Tuisku (1996)	800	791	1067	1252	1079	1220	703	748	884	602
Raith et al. (1983)	796	829	1028	1268	1121	1313	728	838	841	637
Rao et al. (1997)	945	1070	1480	1236	1376	1452	925	1067	1038	898
Sengupta et al. (1999)	900	850	473	1241	877	1027	743	688	925	659
Sharma et al. (1987)	1066	1199	545	1275	1326	1402	997	1129	1130	984
Stephenson (1984)	830	884	751	1282	1073	1317	739	892	814	654
Stuwe and Powell (1989)	785	816	674	1250	1014	1268	657	804	820	535
Stuwe and Powell (1989)	844	918	702	1272	1069	1338	731	931	818	642
Tong and Wilson (2006)	827	861	890	1269	958	1277	730	845	834	641
Ulianov and Kalt (2006)	925	837	1146	1228	1123	1070	807	743	872	745
Warren et al. (2012)	832	848	722	1256	1006	1219	729	822	887	639
William et al. (2000)	774	812	817	1293	1058	1327	642	782	882	513
Zheng et al. (2006)	844	872	898	1271	1089	1276	770	892	893	696
Thomas (2005)	857	890	745	1244	1123	1252	772	846	848	699
Groppo et al. (2007)	776	801	559	1267	786	1210	980	721	725	964
St-Onge and Lucas (1995)	831	877	662	1278	1052	1285	726	886	796	635
Attoh (1998)	732	715	951	1232	1196	1202	617	626	838	475
Baba (1998)	951	1011	1060	1221	1177	1219	909	1002	987	878
Janak et al. (2006)	1142	1069	1686	1208	1136	1218	1070	1023	1036	1066
Jones and Escher (2002)	769	760	1429	1264	1074	1347	797	872	865	732
Klonowska et al. (2015)	1019	897	1074	1221	828	953	806	811	797	745
Lamb et al. (1986)	809	859	734	1281	1049	1314	698	848	866	595
Palmeri et al. (2007)	947	845	1146	1219	955	1008	760	708	839	681
St-Onge and Lucas (1995)	733	732	867	1271	948	1241	608	692	746	461
Ackermand et al. (1987)	870	880	760	1246	1028	1212	779	863	870	708
Liogys and Jenkins (2000)	726	714	734	1261	1012	1200	597	677	837	445
Mukhopadhyay and Bhattachrya (1997)	824	878	864	1284	1078	1333	741	897	893	656
Bohlen and Essene (1978)	833	861	676	1254	1015	1236	729	832	866	639
Tenthorey et al. (1996)	917	814	605	1221	825	919	684	681	871	574
Thost et al. (1991)	912	942	927	1238	1050	1264	849	710	893	801
Bohlen and Essene (1979)	1043	1262	680	1313	1506	1583	818	1118	782	761

Table 5: Models used and their regression values.

Model	$\ln K_D$	R^2
Wood and Banno (1973)	-3428/ T(°C) + 1.787	0.2711
Wells (1977)	- 4734/ T (°C) + 3.316	0.7906
Kretz (1982)	620.8/ T (°C) - 0.243	0.9934
Nickel and Brey (1984)	1021 / T (°C) -1.574	0.0227
Nickel and Green (1985)	- 3783/ T (°C) +1.637	0.9463
Bertrand and Mercier (1985)	- 5330/ T (°C) + 2.903	0.9533
Brey and Kohler (1990)	-2531 / T (°C) +1.084	0.611
Taylor (1998)	- 2571/ T (°C) +0.791	0.3726
Putirka (2008)	- 2809 / T (°C) + 0.867	0.3855
Nimis and Grutter (2010)	- 1118/ T (°C) -0.583	0.5469

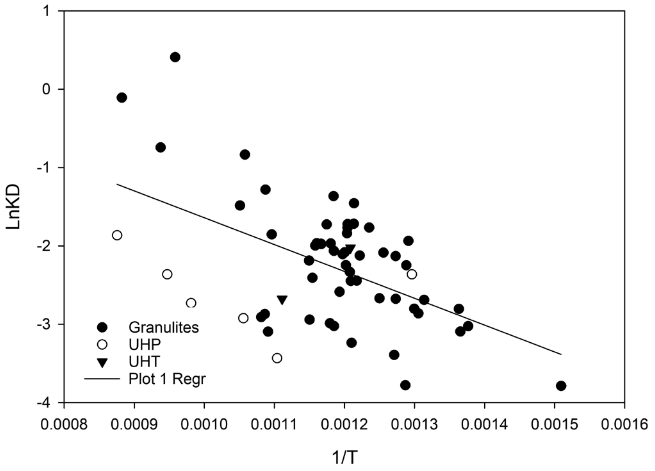

Fig. 1: $\ln K_D$ vs 1/T (Wood and Banno, 1973).

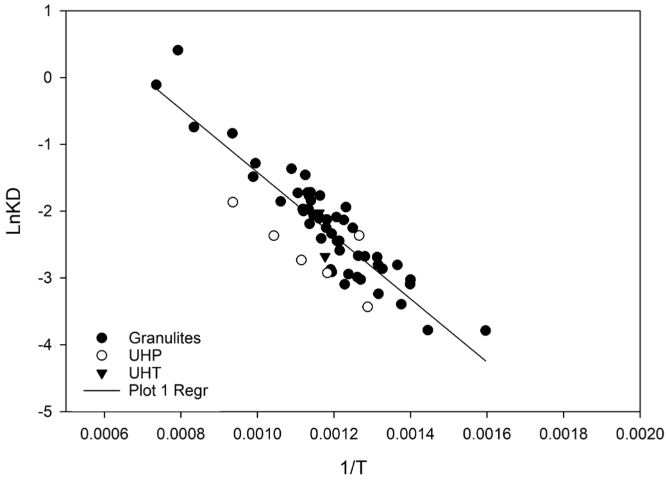

Fig. 2: $\ln K_D$ vs 1/T (Wells, 1977).

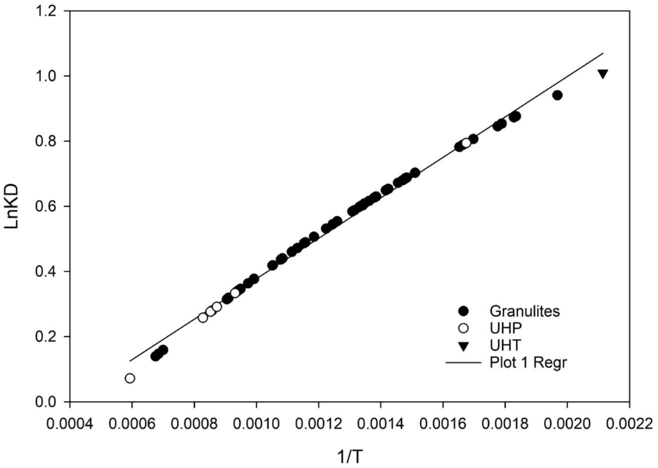

Fig. 3: $\ln K_D$ vs 1/T (Kretz, 1982).

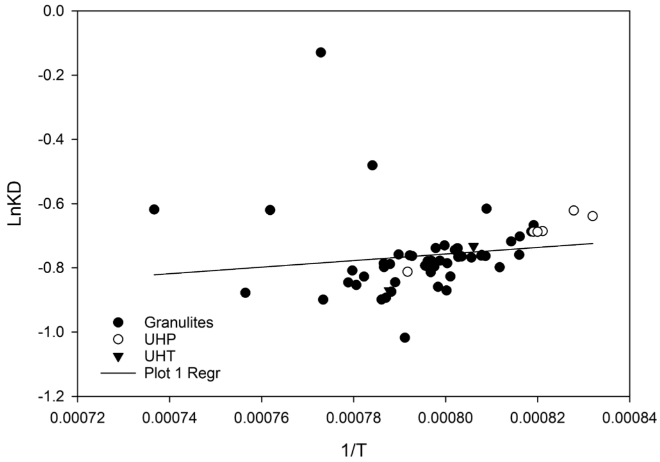

Fig. 4: $\ln K_D$ vs 1/T (Nickel and Brey, 1984).

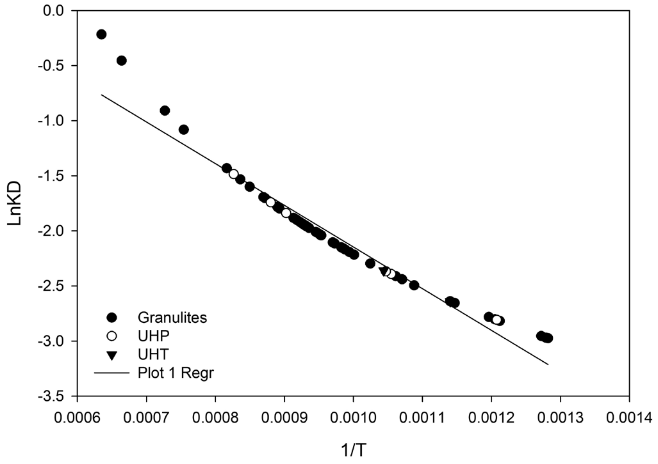

Fig. 5: $\ln K_D$ vs 1/T (Nickel and Green, 1985).

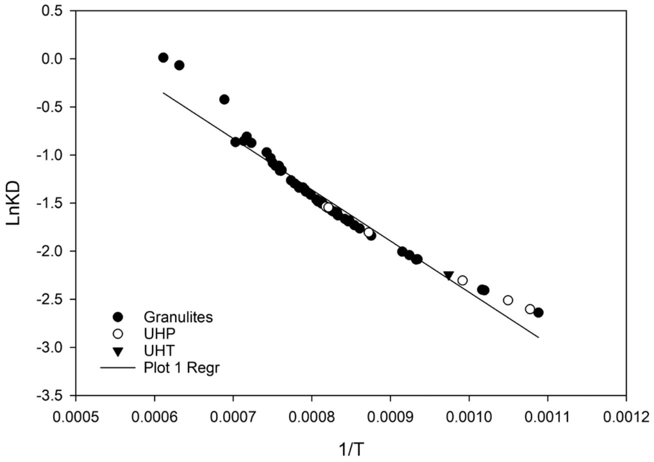

Fig. 6: LnK$_D$ vs 1/T (Bertrend and Merceier, 1986).

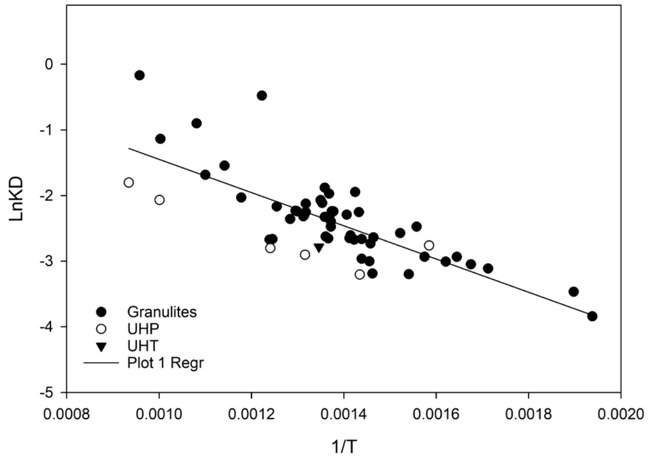

Fig. 7: LnK$_D$ vs 1/T (Brey and Kohler, 1990).

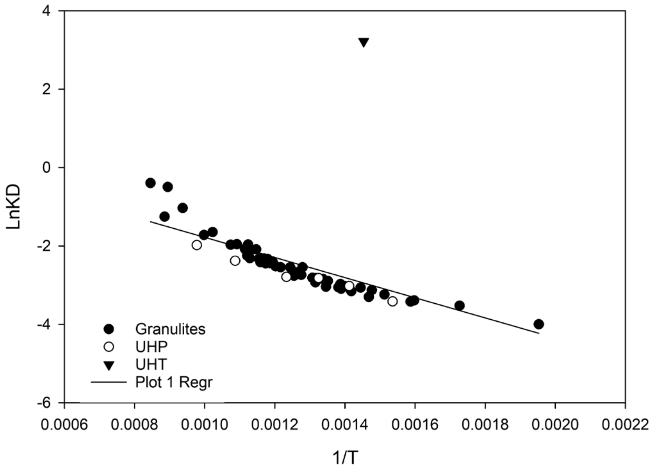

Fig. 8: LnK$_D$ vs 1/T (Taylor, 1998).

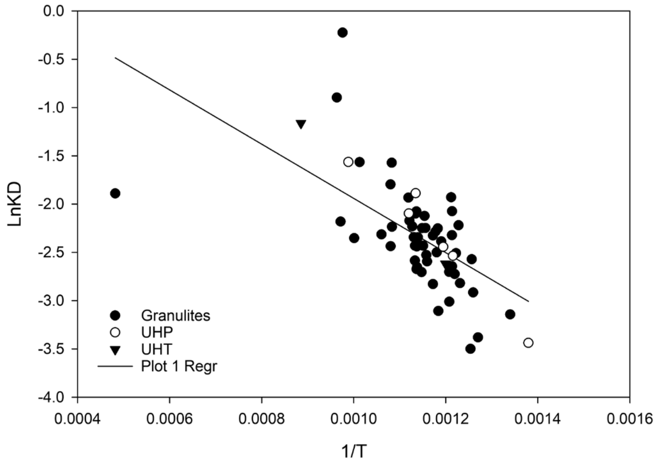

Fig. 9: LnK$_D$ vs 1/T (Putirka, 2008).

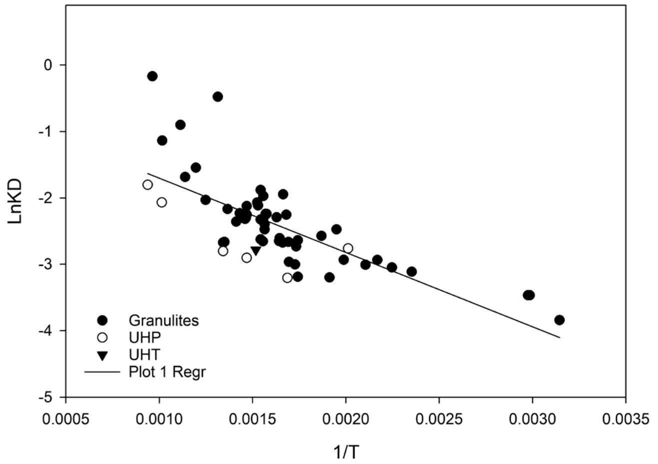

Fig. 10: LnK$_D$ vs 1/T (Nimis and Grutter, 2010).

CONCLUSION

We conclude that the following three Opx-Cpx thermometers Kretz (1982), Bertrend and Mercier (1985) and Nickel and Green (1985) are almost equally valid. These models show the highest regression (Kretz, (1982), R^2 = 0.9934; Bertrend and Mercier (1985), R^2 = 0.9533; Nickel and Green (1985) R^2 = 0.9463) and maximum numbers of points (values of temperature) are providing the best fit lines. Therefore, these models can be considered as the most appropriate ones to be used for the calculation of temperature. The other calibrations gave highly erratic results, hence are not recommended. However, Kretz (1982) is the best among them as the regression correlation coefficient value; R^2 is close to 1. Therefore the temperature value obtained by Kretz (1982) model is more precise compared to the others. Although it is always necessary to do further experimental work to refine the calibration of the Opx-Cpx thermometer with chemical compositions comparable to natural minerals, it is equally important to improve our knowledge of the various chemical interactions within minerals, so that we can improve the activity models for these minerals.

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REFERENCES

Ackermand, D., Herd, R. K., Reinhardt, M., and Windley, B. F. 1987, Sapphirine Parageneses from the Caraiba Complex, Bahia, Brazil: the Influence of Fe^{2+} - Fe^{3+} Distribution on the Stability of Sapphirine in Natural Assemblages. Jour. Meta. Geology, v. 5(3), pp. 323–339.

Appel, P., Möller, A., and Schenk, V., 1998, High-Pressure Granulite Facies Metamorphism in the Pan-African Belt of Eastern Tanzania: P–T–t Evidence against Granulite Formation by Continent Collision. Jour. of Meta. Geology, v. 16(4), pp. 491–509.

Attoh, K., 1998, Models for Orthopyroxene - Plagioclase and other Corona Reactions in Metanorites, Dahomeyideorogen, West Africa. Jour. of Meta. Geology, v. 16(3), pp. 345–362.

Baba, S., 1998, Proterozoic Anticlockwise P–T Path of the Lewisian Complex of South Harris, Outer Hebrides, NW Scotland. Jour. of Meta. Geology, v. 16(6), pp. 819–841.

Baldwin, J. A., Bowring, S. A., and Williams, M. L., 2003, Petrological and Geochronological Constraints on High Pressure, High Temperature Metamorphism in the Snowbird Tectonic Zone, Canada. Jour. of Meta. Geology, v. 21(1), pp. 81–98.

Barnicoat, A. C., 1983, Metamorphism of the Scourian Complex, NW Scotland. Jour. of Meta. Geology, v. 1(2), pp. 163–182.

Barth, A. P. and May, D. J., 1992, Mineralogy and Pressure–Temperature–time Path of Cretaceous Granulite Gneisses, South-Eastern San Gabriel Mountains, Southern California. Journal of Metamorphic Geology, v. 10(4), pp. 529–544.

Berman, R. G., 1991, Thermobarometry using Multi-Equilibrium Calculations: A New Technique, with Petrological Applications. The Canadian Mineralogist, v. 29 (4), pp. 833–855.

Bertrand, P. and Mercier, J. C. C., 1985, The Mutual Solubility of Coexisting Ortho-and Clinopyroxene: Toward an Absolute Geothermometer for the Natural System?. Earth and Planetary Science Letters, v. 76(1-2), pp. 109–122.

Bohlen, S. R. and Essene, E. J. 1979, A Critical Evaluation of Two-Pyroxene Thermometry in Adirondack Granulites. Lithos, v. 12(4), pp. 335–345.

Bohlen, S. R. and Essene, E. J., 1978, Igneous Pyroxenes from Metamorphosed Anorthosite Massifs. Contri. to Mineralogy and Petrology, v. 65(4), pp. 433–442.

Boyd, F. R., 1973, A Pyroxene Geotherm. Geochimica et Cosmochimica Acta, v. 37(12), pp. 2533–2546.

Brey, G. P. and Köhler, T., 1990, Geothermobarometry in Four-Phase Lherzolites II. New Thermobarometers, and Practical Assessment of Existing Thermobarometers. Jour. Petrology, v. 31(6), pp. 1353–1378.

Brodie, K. H., 1995, The Development of Orientated Symplectites During Deformation. Jour. of Meta. Geology, v. 13(4), pp. 499–508.

Carney, J. N., Treloar, P. J., Barton, C. M., Crow, M. J., Evans, J. A., and Simango, S., 1991, Deep-Crustal Granulites with Migmatitic and Mylonitic Fabrics from the Zambezi Belt, Northeastern Zimbabwe. Jour. of Meta. Geology, v. 9(4), pp. 461–479.

Cooke, R. A., 2000, High-Pressure/Temperature Metamorphism in the St. Leonhard Granulite Massif, Austria: Evidence from Intermediate Pyroxene-bearing Granulites. Intern. Jour. Earth Sciences, v. 89(3), pp. 631–651.

Cruciani, G., Franceschelli, M., Groppo, C., and Spano, M. E., 2012, Metamorphic Evolution of Non-Equilibrated Granulitised Eclogite from Punta de li Tulchi (Variscan Sardinia) Determined through Texturally Controlled Thermodynamic Modelling. Jour. of Meta. Geology, v. 30(7), pp. 667–685.

Daczko, N. R. and Halpin, J. A., 2009, Evidence for Melt Migration Enhancing Recrystallization of Metastable Assemblages in Mafic Lower Crust, Fiordland, New Zealand. Jour. of Meta. Geology, v. 27(2), pp. 167–185.

Dasgupta, S., Sengupta, P., Fukuoka, M., and Chakraborti, S., 1992, Dehydration Melting, Fluid Buffering and Decompressional P–T Path in a Granulite Complex from the Eastern Ghats, India. Jour. of Meta. Geology, v. 10(6), pp. 777–788.

Ellis, D. J. and Green, D. H., 1985, Garnet-Forming Reactions in Mafic Granulites from Enderby Land, Antarctica - Implications for Geothermometry and Geobarometry. Jour. Petrology, v. 26(3), pp. 633–662.

EL-Shazly, A. K., Loehn, C., and Tracy, R. J., 2011, P–T–t Evolution of Granulite Facies Metamorphism and Partial Melting in the Winding Stair Gap, Central Blue Ridge, North Carolina, USA. Jour. Meta. Geology, v. 29(7), pp. 753–780.

Elvevold, S., Thrane, K., and Gilotti, J. A., 2003, Metamorphic History of high-pressure granulites in Payer Land, Greenland Caledonides. Jour. Meta. Geology, v. 21(1), pp. 49–63.

Engvik, A. K., Tveten, E., Bingen, B., Viola, G., Erambert, M., Feito, P., and De Azavedo, S., 2007, P–T–t Evolution and Textural Evidence for Decompression of Pan-African High-Pressure Granulites, Lurio Belt, North-Eastern Mozambique. Jour. Meta. Geology, v. 25(9), pp. 935–952.

Ferry, J. M. and Watson, E. B., 2007, New Thermodynamic Models and Revised Calibrations for the Ti-in-zircon and Zr-in-Rutile Thermometers. Contri. Mineralogy and Petrology, v. 154(4), pp. 429–437.

Ferry, J. T. and Spear, F. S., 1978, Experimental Calibration of the Partitioning of Fe and Mg Between Biotite and Garnet. Contri. Mineralogy and Petrology, v. 66(2), pp. 113–117.

Fu, B., Zheng, Y. F., Li, Y. L., and Li, S. G., 1998, Applications of Garnet–Clinopyroxene Geothermometers to Eclogite Assemblages. Acta Mineralogica Sinica, v. 18, pp.145–157.

Gallien, F., Mogessie, A., Hauzenberger, C. A., Bjerg, E., Delpino, S., and Castro de Machuca, B., 2012, On the Origin of Multi-Layer Coronas Between Olivine and Plagioclase at the Gabbro - Granulite Transition, Valle Fértil–La Huerta Ranges, San Juan Province, Argentina. Jour. of Meta. Geology, v. 30(3), pp. 281–302.

Garde, A. A., 1990, Thermal Granulite-Facies Metamorphism with Diffuse Retrogression in Archaean Orthogneisses, Fiskefjord, Southern West Greenland. Jour. of Meta. Geology, v. 6, pp. 663–682.

Gasparik, T., 1984, Two-Pyroxene Jour. of Meta. Geology Thermobarometry with New Experimental Data in the System CaO-MgO-Al_2O_3-SiO_2. Contri. Mineralogy and Petrology, v. 87(1), pp. 87–97.

Goto, A. and Banno, S., 1990, Hydration of Basic Granulite to Garnet-Epidote Amphibolite in the Sanbagawa Metamorphic

Belt, Central Shikoku, Japan. Chemical geology, v. 85(3-4), pp. 247–263.

Grant, S. M., 1989, Tectonic implications from sapphirine-bearing lithologies, south-west Grenville Province, Canada. Jour. Metamorphic Geology, v. 7(6), pp. 583–598.

Griffin, W. L., Carswell, D. A., Nixon, P. H., Boyd, F. R., and Meyer, H. O. A., 1979, Lower crustal granulites and eclogites from Lesotho southern Africa. In The Mantle Sample. American Geophysics Union Washington, DC. v. 2, pp. 59–86.

Groppo, C., Lombardo, B., Rolfo, F., and Pertusati, P., 2007, Clockwise Exhumation Path of Granulitized Eclogites from the Ama Drime Range (Eastern Himalayas). Jour. Meta. Geology, v. 25(1), pp. 51–75.

Harley, S. L., 1988, Proterozoic Granulites from the Rauer Group, East Antarctica. I. Decompressional Pressure-Temperature Paths Deduced from Mafic and Felsic Gneisses. Jour. of Petrology, v. 29(5), pp. 1059–1095.

Holdaway, M. J., 2001, Recalibration of the GASP Geobarometer in Light of Recent Garnet and Plagioclase Activity Models and Versions of the Garnet-Biotite Geothermometer. American Mineralogist, v. 86(10), pp. 1117–1129.

Jamtveit, B., Carswell, D. A., and Mearns, E. W., 1991, Chronology of the high-pressure metamorphism of Norwegian Garnet Peridotites/Pyroxenites. Jour. Meta. Geology, v. 9(2), pp. 125–139.

Janak, M., Froitzheim, N., Vrabec, M., Krogh Ravna, E. J., and De Hoog, J. C. M., 2006, Ultrahigh-Pressure Metamorphism and Exhumation of Garnet Peridotite in Pohorje, Eastern Alps. Jour. Meta. Geology, v. 24(1), pp. 19–31.

Johnson, C. A., Bohlen, S. R., and Essene, E. J., 1983, An Evaluation of Garnet-Clinopyroxene Geothermometry in Granulites. Contri. Mineralogy and Petrology, v. 84 (2-3), pp. 191–198.

Jones, K. A. and Escher, J. C., 2002, Near-Isothermal Decompression within a Clockwise P–T Evolution Recorded in Migmatitic Mafic Granulites from Clavering Ø, NE Greenland: Implications for the Evolution of the Caledonides. Jour. Meta. Geology, v. 20(3), pp. 365–378.

Joshi, M., Thomas, H., and Sharma, R. S., 1993, Granulite Facies Metamorphism in the Archaean Gneiss Complex from North-Central Rajasthan. Proceedings-National Academy of Sciences India Section A, v. 63, pp. 167–167.

Kardarusman, A. and Parkinson, C. D., 2000, Petrology and PT Evolution of Garnet Peridotites from Central Silawesi. Indonesia. Jour. Meta. Geology, v. 18, pp. 193–209.

Klonowska, I., Janák, M., Majka, J., Froitzheim, N., and Kośmińska, K., 2015, Eclogite and Garnet Pyroxenite from Stor Jougdan, Seve Nappe Complex, Sweden: Implications for UHP Metamorphism of Allochthons in the Scandinavian Caledonides. Jour. Meta. Geology, v. 34(2), pp. 103–119.

Köhler, T. P. and Brey, G., 1990, Calcium Exchange between Olivine and Clinopyroxene Calibrated as a Geothermobarometer for Natural Peridotites from 2 to 60 kb with Applications. Geochimica et Cosmochimica Acta, v. 54(9), pp. 2375–2388.

Kretz, R., 1982, Transfer and Exchange Equilibria in a Portion of the Pyroxene Quadrilateral as Deduced from Natural and Experimental Data. Geochimica et Cosmochimica Acta, v. 46(3), pp. 411–421.

Lamb, R. C., Smalley, P. C., and Field, D., 1986, P–T Conditions for the Arendal Granulites, Southern Norway: Implications for the Roles of P, T and CO_2 in Deep Crustal LILE-Depletion. Jour. Meta. Geology, v. 4(2), pp. 143–160.

Liangzhao, L. and Shiqin, J., 1993, P–T–t Paths and Tectonic History of an Early Precambrian Granulite Facies Terrane, Jining District, South-East Inner Mongolia, China. Jour. Meta. Geology, v. 11(4), pp. 483–498.

Lindsley, D. H., 1983, Pyroxene Thermometry. American Mineralogist, v. 68(5-6), pp. 477–493.

Liogys, V. A. and Jenkins, D. M., 2000, Hornblende Geothermometry of Amphibolite Layers of the Popple Hill Gneiss, North-West Adirondack Lowlands, New York, USA. Jour. Meta. Geology, v. 18(5), pp. 513–530.

Loock, G., Stosch, H. G., and Seck, H. A., 1990, Granulite facies lower crustal xenoliths from the Eifel, West Germany: petrological and geochemical aspects. Contri. Mineralogy and Petrology, v. 105(1), pp. 25–41.

Lucassen, F. and Franz, G., 1996, Magmatic arc metamorphism: petrology and temperature history of metabasic rocks in the Coastal Cordillera of northern Chile. Jour. Meta. Geology, v. 14(2), pp. 249–265.

Mahan, K. H., Goncalves, P., Flowers, R., Williams, M. L., and Hoffman-Setka, D., 2008, The Role of Heterogeneous Strain in the Development and Preservation of a Polymetamorphic Record in High-P Granulites, Western Canadian Shield. Jour. Meta. Geology, v. 26(6), pp. 669–694.

Marschall, H. R., Kalt, A., and Hanel, M., 2003, P–T Evolution of a Variscan Lower-Crustal Segment: A Study of Granulites from the Schwarzwald, Germany. Jour. Petrology, v. 44(2), pp. 227–253.

Muhling, J. R., 1990, The Narryer Gneiss Complex of the Yilgarn Block, Western Australia: a Segment of Archaean Lower Crust Uplifted During Proterozoic Orogeny. Jour. Meta. Geology, v. 8(1), pp. 47–64.

Muhongo, S. and Tuisku, P., 1996, Pan-African High Pressure Isobaric Cooling: Evidence from the Mineralogy and Thermobarometry of the Granulite-Facies Rocks from the Uluguru Mountains, eastern Tanzania. Jour. African Earth Sciences, v. 23(3), pp. 443–463.

Mukhopadhyay, A. K. and Bhattachrya, A. 1997, Tectonothermal Evolution of the Gneiss Complex at Salur in the Eastern Ghats Grnaulite Belt of India. Jour. Meta. Geology, v. 15(6), pp. 719–734.

Nickel, K. G. and Brey, G., 1984, Subsolidus Orthopyroxene - Clinopyroxene Systematics in the System CaO-MgO-SiO_2 to 60 kb: a Re-evaluation of the Regular Solution Model. Contrib. Mineralogy and Petrology, v. 87(1), pp. 35–42.

Nickel, K. G. and Green, D. H., 1985, Empirical Geothermobarometry for Garnet Peridotites and Implications for the Nature of the Lithosphere, Kimberlites and Diamonds. Earth and Planetary Science Letters, v. 73(1), pp. 158–170.

Nimis, P. and Grütter, H., 2010, Internally Consistent Geothermometers for Garnet Peridotites and Pyroxenites. Contri. Mineralogy and Petrology, v. 159(3), pp. 411–427.

Palmeri, R., Ghiribelli, B., Ranalli, G., Talarico, F., and Ricci, C. A., 2007, Ultrahigh-Pressure Metamorphism and Exhumation of Garnet-bearing Ultramafic Rocks from the Lanterman Range (northern Victoria Land, Antarctica). Jour. Meta. Geology, v. 25(2), pp. 225–243.

Powell, R. and Holland, T., 1994, Optimal Geothermometry and Geobarometry. American Mineralogist, v. 79(1-2), pp. 120–133.

Putirka, K. D., 2008, Thermometers and barometers for volcanic systems. Reviews in mineralogy and geochemistry, v. 69 (1), pp. 61–120.

Raith, M., Raase, P., Ackermand, D., and Lal, R. K., 1983, Regional Geothermobarometry in the Granulite Facies Terrane of South

India. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, v. 73(4), pp. 221–244.

Rao, D. R., Sharma, R., and Gururajan, N. S., 1997, Mafic Granulites of the Schirmcher Region, East Antarctica: Fluid Inclusion and Geothermobarometric Studies Focusing on the Proterozoic Evolution of the Crust. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, v. 88(1), pp. 1–17.

Saxena, S. K. and Nehru, C. E., 1975, Enstatite - Diopside Solvus and Geothermometry. Contri. Mineralogy and Petrology, v. 49(3), pp. 259–267.

Saxena, S. K., 1976, Two-Pyroxene Geothermometer; A Model with An Approximate Solution. American Mineralogist, v. 61(7-8), pp. 643–652.

Sengupta, P., Sen, J., Dasgupta, S., Raith, M., Bhui, U. K., and Ehl, J., 1999, Ultra-High Temperature Metamorphism of Metapelitic Granulites from Kondapalle, Eastern Ghats Belt: Implications for the Indo-Antarctic Correlation. Jour. of Petrology, v. 40(7), pp. 1065–1087.

Sharma, R. S., Sills, J. D., and Joshi, M., 1987, Mineralogy and Metamorphic History of Norite Dykes within Granulite Facies Gneisses from Sand Mata, Rajasthan, NW India. Mineralogical Magazine, v. 51(360), pp. 207–215.

Stephenson, N. C. N., 1984, Two-Pyroxene Thermometry of Precambrian Granulites from Cape Riche, Albany-Fraser Province, Western Australia. Jour. Meta. Geology, v. 2(4), pp. 297–314.

St-Onge, M. R. and Lucas, S. B., 1995, Large-Scale Fluid Infiltration, Metasomatism and Re-equilibration of Archaean Basement Granulites during Palaeo-Proterozoic Thrust Belt Construction, Ungava Orogen, Canada. Jour. of Meta. Geology, v. 13(4), pp. 509–535.

Stüwe, K. and Powell, R., 1989, Low-Pressure Granulite Facies Metamorphism in the Larsemann Hills Area, East Antarctica; Petrology and Tectonic Implications for the Evolution of the Prydz Bay area. Jour. Meta. Geology, v. 7(4), pp. 465–483.

Stüwe, K. and Powell, R., 1989, Metamorphic Evolution of the Bunger Hills, East Antarctica: Evidence for Substantial Post-Metamorphic Peak Compression with Minimal Cooling in a Proterozoic Orogenic Event. Jour. Meta. Geology, v. 7(4), pp. 449–464.

Taylor, W. R., 1998, An Experimental Test of Some Geothermometer and Geobarometer Formulations for Upper Mantle Peridotites with Application to the Thermobarometry of Fertile Lherzolite and Garnet Websterite. Neues Jahrbuchfür Mineralogie-Abhandlungen, pp. 381–408.

Tenthorey, E. A., Ryan, J. G., and Snow, E. A., 1996, Petrogenesis of Sapphirine-bearing Metatroctolites from the Buck Creek Ultramafic Body, Southern Appalachians. Jour. Metam. Geology, v. 14(2), pp. 103–114.

Thomas, H. and Rana, H., 2019, Valid Garnet-Biotite Thermometer: A Comparative Study. Jour. Nepal Geol. Soc. v. 58, pp. 61–68.

Thomas, H. and Rana, H., 2020, Garnet-Hornblende Geothermometer: A Comparative Study. Jour. of the Geol. Soc. India, v. 96(6), pp. 591–596.

Thomas, H., 1994, Announcement of Software MPET. Developed Software "MPET" for Calculation of P-T and Activities of Common Metamorphic Minerals Based on Different Models Published in Recent Years. Jour. Geol. Soc. India, v. 44.

Thomas, H., 2005, Polymetamorphism in the Archaean Gneiss Complex of Shivpura-Gyangarh, District Bhilwara, Rajasthan. Ed. H.Thomas, Metamorphism and Crustal Evolution. Atlantic Publishers and Distributors, New Delhi, pp. 123–147.

Thomas, H., Rana, H., and Anju, M., 2020, Applicability of Garnet-Cordierite (GCRD) Geothermometer. Jour. Nepal Geol. Soc. v. 60, pp. 147–161.

Thomas, H., Rana, H., and Shahid, M., 2018, Garnet-Orthopyroxene (GOPX) Geothermometer: a Comparative Study. Arabian Jour. Geosciences, v. 11(24), pp. 771.

Thomas, J. B., Watson, E. B., Spear, F. S., Shemella, P. T., Nayak, S. K., and Lanzirotti, A., 2010, TitaniQ Under Pressure: the Effect of Pressure and Temperature on the Solubility of Ti in Quartz. Contri. to Mineralogy and Petrology, v. 160(5), pp.743–759.

Thost, D. E., Hensen, B. J., and Motoyoshi, Y., 1991, Two-Stage Decompression in Garnet-bearing Mafic Granulites from Sostrene Island, Prydz Bay, East Antarctica. Jour. Meta. Geology, v. 9(3), pp. 245–256.

Tong, L. and Wilson, C. J., 2006, Tectonothermal Evolution of the Ultrahigh Temperature Metapelites in the Rauer Group, East Antarctica. Precambrian Research, v. 149 (1-2), pp. 1–20.

Ulianov, A. and Kalt, A., 2006, Mg-Al Sapphirine-and Ca-Al Hibonite-bearing Granulite Xenoliths from the Chyulu Hills Volcanic Field, Kenya. Jour.of Petrology, v. 47(5), pp. 901–927.

Wark, D. A. and Watson, E. B., 2006, TitaniQ: A Titanium-in-Quartz Geothermometer. Contri. to Mineralogy and Petrology, v. 152(6), pp. 743–754.

Wark, D. A., Anderson, A. T., and Watson, E. B., 2004, Probing Ti in quartz: Application of the TITANiQ Thermometer to the Bishop Tuff. AGUSM, V34B-04.

Warren, C. J., Grujic, D., Cottle, J. M., and Rogers, N. W., 2012, Constraining Cooling Histories: Rutile and Titanite Chronology and Diffusion Modelling in NW Bhutan. Jour. of Meta. Geol., v. 30(2), pp. 113–130.

Watson, E. B., Wark, D. A., and Thomas, J. B., 2006, Crystallization Thermometers for Zircon and Rutile. Contri. to Mineralogy and Petrology, v. 151(4), p. 413.

Wells, P. R., 1977, Pyroxene Thermometry in Simple and Complex Systems. Contri. to mineralogy and Petrology, v. 62(2), pp. 129–139.

Williams, M. L., Melis, E. A., Kope, C. F., and Hanmer, S., 2000, Microstructural Tectono Metamorphic Processes and the Development of Gneissic Layering: a Mechanism for Metamorphic Segregation. Jour. of Meta. Geology, v. 18(1), pp. 41–58.

Wood, B. J. and Banno, S., 1973, Garnet-Orthopyroxene and Orthopyroxene-Clinopyroxene Relationships in Simple and complex systems. Contri. to Mineralogy and Petrology, v. 42(2), pp. 109–124.

Yoshida, D., Hirajima, T., and Ishiwatari, A., 2004, Pressure-Temperature Path Recorded in the Yangkou Garnet Peridotite, in Su-Lu Ultrahigh - Pressure Metamorphic Belt, Eastern China. Jour. of Petrology, v. 45(6), pp. 1125–1145.

Zheng, J., Griffin, W. L., O'Reilly, S. Y., Zhang, M., Liou, J. G., and Pearson, N., 2006, Granulite Xenoliths and Their Zircons, Tuoyun, NW China: Insights into South-Western Tianshan Lower Crust. Precambrian Research, v. 145(3-4), pp. 159–181.